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Velocity and Drop Size Measurements in a Swirl-Stabilized, Combusting Spray

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VELOCITY AND DROP SIZE MEASUREMENTS IN A SWIRL-STABILIZED, COMBUSTING SPRAY

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ABSTRACT

Velocity and drop size measurements are reported for a swirl-stabilized, combusting spray. For the gas phase, three components of mean and fluctuating velocity are reported. For the droplets, three components of mean and fluctuating velocity, diameter, and number flux are reported. The liquid fuel utilized for all the tests was heptane. The fuel was injected using an air-assist atomizer. The combustor configuration consisted of a center-mounted, air-assist atomizer surrounded by a coflowing air stream. Both the coflow and the atomizing air streams were passed through 45 degree swirlers. The swirl was imparted to both streams in the same direction. The combustion occurred unconfined in stagnant surroundings. The nonintrusive measurements were obtained using a two-component phase/Doppler particle analyzer. The laser-based instrument measured two components of velocity as well as droplet size at a particular point. Gas phase measurements were obtained by seeding the air streams with nominal 1 micron size aluminum-oxide particles and using the measured velocity from that size to represent the gas phase velocity. The atomizing air, coflow air and ambient surroundings were all seeded with the aluminum-oxide particles to prevent biasing. Measurements are reported at an axial distance of 5 mm from the nozzle. Isothermal single-phase gas velocities are also reported for comparison with the combusting case.

1.INTRODUCTION

Combusting sprays are very important for gas turbine engine applications. The investigation of combusting sprays should lead to a better understanding of the physics involved in this complicated process. Important processes involved in combusting sprays are the interactions between the droplets and the gas phase, the vaporization of the droplets, and chemical reactions with heat release. These physical processes are coupled and can only be completely described using numerical modeling. As part of an effort to improve the numerical modeling of gas turbine combustors, an experimental study has been undertaken to obtain a data set for a relatively simple liquid-fueled combustor that can be used for comparison with numerical models.

Because of their practical applications, swirling flows with combustion have been studied by a large number of investigators. Earlier reviews of swirling flows both with and without combustion present some general trends.[1-3] These papers predate the development of non-intrusive, laser-based diagnostics; consequently all of the results described were obtained using instrusive instrumentation and detailed structure measurements for these types of flows were not possible. With the advent of newer instrumentation techniques, namely laser Doppler anemometry, additional details of the structure of these types of flows began to emerge. Laser Doppler anemometry velocity measurements in spray flames[4,5] reveal some of the flowfield structure of swirling flames. The development of the phase/Doppler particle analyzer,[6] enabled the simultaneous measurement of droplet size and velocity. This instrument has been used by a number of investigators for measurements in spray flames in a variety of configurations.[7-11] This instrument has the capability to measure velocities of both the gas and droplet phases in a combusting spray.

2.EXPERIMENT

The combustor utilized in the present experiment is illustrated in figure 1. It consists of a center mounted air-assist fuel nozzle, Parker Hannifin research simplex air-assist atomizer, surrounded by a coflowing air stream. The nozzle orifice diameter was 4.8 mm. Both the air assist and the coflow air streams had swirl imparted to them using 45 degree swirlers. The swirlers were constructed by machining 45 degree slots into rings. Both streams were swirled in the same direction for the present study. The combustion air was not preheated and entered the combustor at 297 K. The top of the air-assist nozzle was water cooled to prevent overheating of an O-ring in the nozzle assembly. The temperatures of the fuel, atomizing air and coflow air streams were measured using Chromal Alumel thermocouples. Flow rates of the air streams were measured using calibrated orifices and the fuel flow rate was measured using a mass flowmeter. All results reported in the present study are reported for a coflow air flow rate of 13.88 g/s, an air-assist flow rate of 0.96 g/s, and a fuel flow rate of 0.38 g/s. The fuel used was heptane. The coflow stream entered the combustor in three radial locations, passed through a honeycomb flow straightener, and the swirlers before exiting the combustor. The swirler was located 140 mm upstream of the combustor exit. The flow from the combustor discharged into ambient, stagnant surroundings.

The combustor was mounted vertically within a large (1.8 m square by 2.4 m high) enclosure. The entire enclosure was mounted on two sets of linear bearings and was traversed using stepper motors to provide motion in two directions. The combustor assembly itself could be traversed in the vertical direction using a third stepper motor to allow measurements at all locations in the flowfield. This arrangement allowed rigid mounting of all optical components.

The phase/Doppler particle analyzer was used for all measurements reported in this study. A schematic of the two-component instrument is shown in figure 2. The beam from a 6 watt Argon-Ion laser is split into 488.0 and 514.5 nm wavelengths using a dichroic mirror. Each beam is then focused onto a rotating diffraction grating which splits each beam into several pairs. The two first-order beams for each wavelength are then recombined onto the optical axis using a dichroic mirror, collimated and focused at a point to form the two-component probe volume. In the present study, the transmitting optics utilized a 500 mm focal length lens. The receiving optics were located 30 degrees off axis in the forward-scatter direction. Light was collected using a 500 mm focal-length lens and then focused onto a 100 micron by 1 mm long slit. The collected light is then split and picked up by 4 photodetectors. Three are arranged to look at the signals from the 514.5 beams and one receives light from the 488 nm beams. Each of the three photodetectors for the green beams are imaged at a different area of the collection lens and the phase difference between the signals is used for the size determination. Details of the instrument can be found in reference 6.

In the present study, velocities of both the liquid and gaseous phases were measured. This was accomplished by seeding the gas phase with nominal 1 micron size aluminum-oxide particles. The coflow, air-assist flow, and the ambient surroundings were all seeded to minimize biasing. Phase discrimination is inherent in the instrumentation with the ability to size each measured particle. At each spatial location, two measurements were taken in order to accurately measure the velocity of each phase. A threshold voltage for the photodetectors at the specified laser power was determined experimentally, below which signals from the aluminum-oxide particles were not detected. For the droplet measurements, the photodetector voltage was kept below this threshold value in order to eliminate interference from the aluminum-oxide particles. Total laser power for all wavelengths was fixed at 1.5 watts for all the measurements. Particles with diameters less than 2.4 microns were used to represent the gas phase velocity. Two complete traverses were taken in order to measure all three components of velocity and provide a check on flow symmetry. Each traverse measured axial velocity and either radial or angular velocity. Generally, 64000 measurement attempts were made at each measurement location. The percentage of measurements actually validated depended on the number density and velocities of drops at each location and ranged from about 65 to 90 percent.

3.RESULTS AND DISCUSSION

In the present study, results are presented for a single axial location at 5 mm downstream of the nozzle. Gas phase results for mean velocities are presented in figure 3(a-c) for isothermal, single-phase flow without droplets and two-phase flow with combustion. Mean gas phase axial velocity, presented in figure 3a, presents results from a complete traverse across the combustor and illustrates the symmetry of the flowfield. The combustor exit dimensions are illustrated on the x-axis of the figure for reference. A small recirculation zone is evident near the center of the nozzle. At this axial location relatively close to the nozzle, velocity gradients are extremely large in the flow from the air-assist stream containing the droplets. Effects of combustion on the flowfield are significant. Both the maximun and minimum mean axial velocities are increased for the combusting case compared to the isothermal case due to the gas expansion associated with the heat release. For the case with combustion, velocities increase from nearly zero to 35 m/s and then decrease to -30 m/s within a radius of about 12 mm. Mean axial velocities in the coflow stream are not affected by the combustion at this axial location.

Figure 3b presents mean radial velocity for the gas phase. As shown in figure 3b, effects of combustion are very dramatic for radial velocity. Maximum radial velocities increased from about 10 m/s for the isothermal case to about 40 m/s for the case with combustion due to the radial expansion of the gas. Again, the gas from the coflow stream is not affected by the combustion at this axial location.

Mean gas phase angular velocities are presented in figure 3c. For this case, reaction and the presence of droplets decreases the maximum angular velocities in the flowfield. Some of the decrease in angular velocity for the gas phase can be attributed to the momentum transferred to the droplets since they do not initially have a swirl component.

Fluctuating gas phase velocities are presented in figure 4(a-c) for both the single-phase, isothermal and the two-phase, combusting cases. All fluctuating velocities presented are root-mean-squared (rms) values. Figure 4a presents radial profiles of gas phase fluctuating axial velocity. Maximum values of fluctuating axial velocity are similar for both the combusting and isothermal cases. The case with combustion does show larger values of axial rms velocity at radial locations between approximately 5 and 15 mm from the center of the nozzle. Axial velocities are also higher at these locations for the combusting case, see figure 3a. Fluctuating radial velocities, illustrated in figure 4b, show dramatic differences between the isothermal and combusting cases. The maximum velocity locations have shifted radially outward corresponding to the shift in mean radial velocity, see figure 3b. The maximum fluctuating radial velocity has also increased from about 10 m/s to 15 m/s.

Fluctuating angular gas phase velocities are presented in figure 4c. Similar to the results shown for mean angular gas phase velocities, fluctuating angular velocities generally decreased with combustion and the presence of the liquid phase compared to the single-phase, isothermal case. A small region from a radius of about 7 to 15 mm shows increased values of fluctuating angular velocity for the case with combustion.

Mean velocities for the drops are presented in figure 5(a-c) for the case with combustion. In the experimental study, velocities were measured for drop sizes ranging from 4 to 142 microns. Results are presented for drop sizes of 15, 32 and 52 microns. Measured gas phase velocities are also presented in the figure. Note that results are only illustrated from -15 to +15 mm for the radial direction because no drops were present at larger radial locations. Figure 5a presents mean drop axial velocity at 5 mm downstream. Similar to the results previously shown for the gas phase, the flowfield is very symmetric. Axial velocity is correlated with drop size in all regions. In the main region of the spray, at a radius of about 7 mm, the maximum velocity of the gas phase was about 38 m/s, and about 28 m/s for the 32 micron drops. Even the maximum velocity of the 15 micron drops lagged the gas phase by about 5 m/s. In the center of the flowfield is a small recirculation zone, see figure 3a. There, only the 15 micron drops showed negative axial velocities while larger drops had positive velocities.

Mean drop radial velocities are presented in figure 5b. Again, there is a correlation between drop size and velocity in the flowfield. Maximum mean radial velocities are slightly higher than maximum axial velocities for the drops due to the heat release and radial expansion of the gas. Mean angular velocities of the drops are presented in figure 5c. Angular velocity is not as symmetric and is also much smaller than the other two components of velocity. The mean drop angular velocity is a strong function of the drop size with the smaller drops showing the least velocity difference with the gas phase.

Fluctuating droplet axial, radial, and angular velocity components for the three drop sizes and gas phase are presented in figure 6(a-c), respectively. The fluctuating drop velocities presented are root-mean-squared (rms) values. Generally, the smaller drops are affected more by the gas phase turbulence and have larger fluctuating velocities than the larger drops. Velocity fluctuations are clearly not isotropic since fluctuating axial and radial velocities are considerably larger than fluctuating angular velocities.

In addition to drop mean and fluctuating velocities, the liquid volume flux is important in two-phase flows. Drop number-flux measurements are presented in figure 7, where results are illustrated for four drop size groups. As shown in figure 7, the positive radial direction has a slightly higher number flux than the negative direction. The results show that smaller droplets have much larger number fluxes. The distribution of the larger droplets is still very important since much of the liquid mass is contained in the larger droplets. Relatively few drops are found in the center region of the flowfield due to the 45 degree swirler that is used in the air-assist stream.

4.CONCLUSIONS

The present study has utilized a two-component phase/Doppler particle analyzer to characterize the structure of a combusting spray. Results are presented at an axial location of 5 mm downstream of the nozzle. The measurements included all three mean and fluctuating components of gas phase velocity. Three mean and fluctuating components of drop velocity for three drop sizes are also presented. In addition, drop number flux was also presented for four drop size groups. The results illustrate the importance of measuring both size and velocity in two-phase, reacting flowfields. A clear correlation of drop velocity with size was evident. As expected, the larger droplets tend to lag the gas phase velocity by a larger amount than smaller drops. Smaller drops were affected more by gas phase turbulence, which was reflected in higher values of fluctuating velocity for smaller drops than larger drops.

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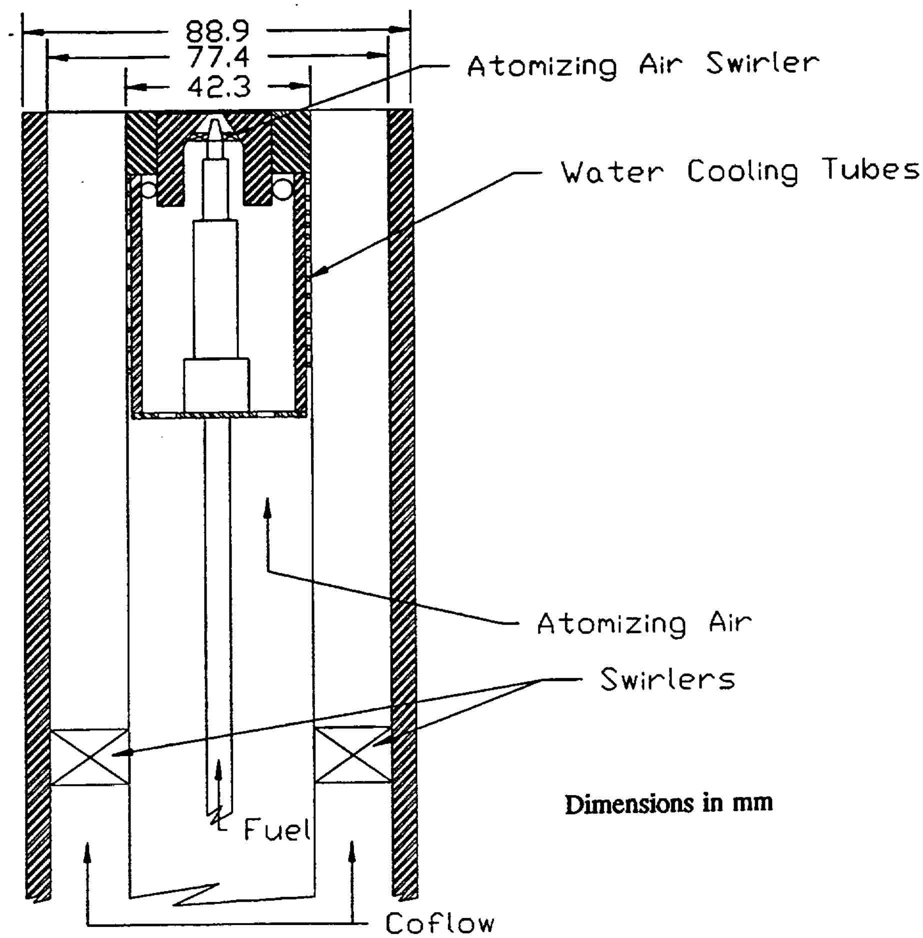

Figure 1.- Schematic drawing of the combustor.

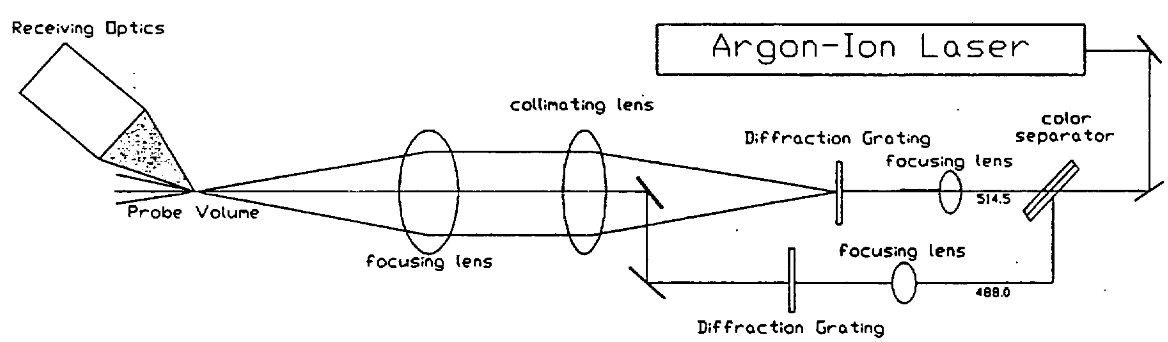

Figure 2.- Optical configuration of the phase/Doppler particle analyzer.

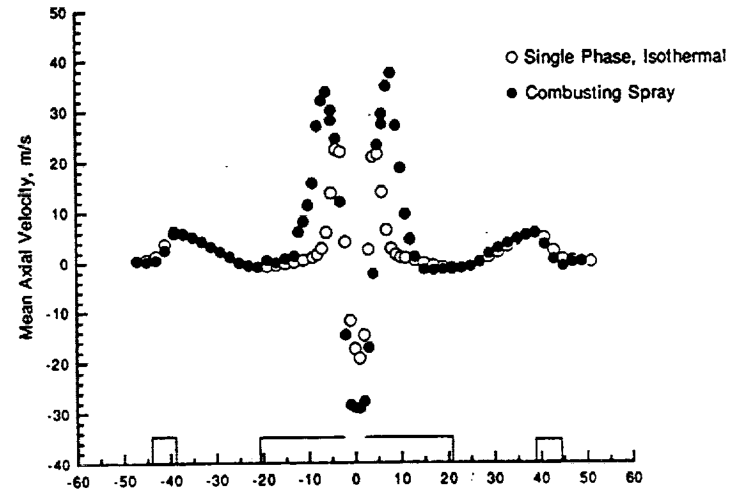

Figure 3a.- Mean axial velocity.

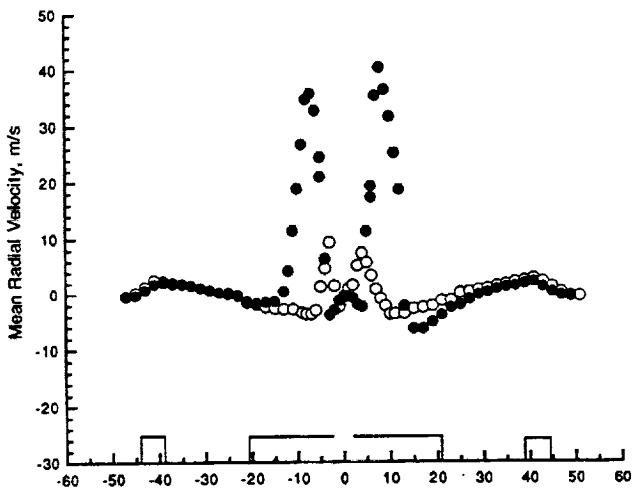

Figure 3b.- Mean radial velocity.

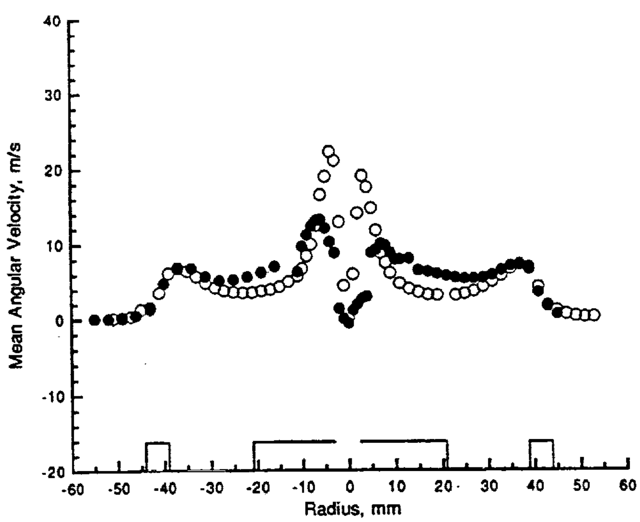

Figure 3c.- Mean angular velocity.

Figure 3.- Gas phase mean velocity at 5 mm downstream.

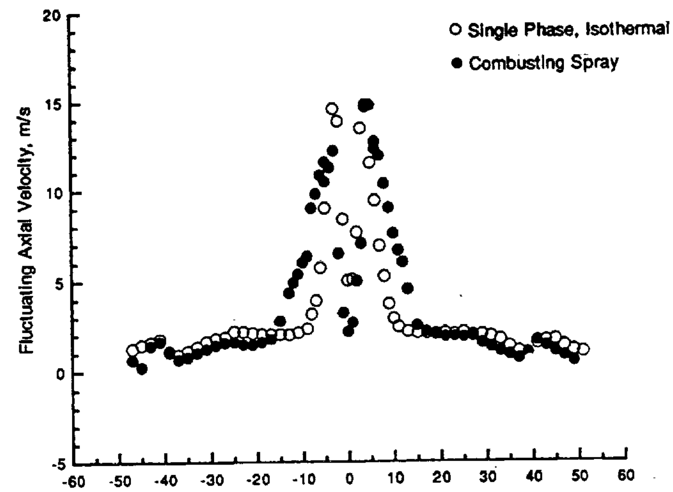

Figure 4a.- Fluctuating axial velocity.

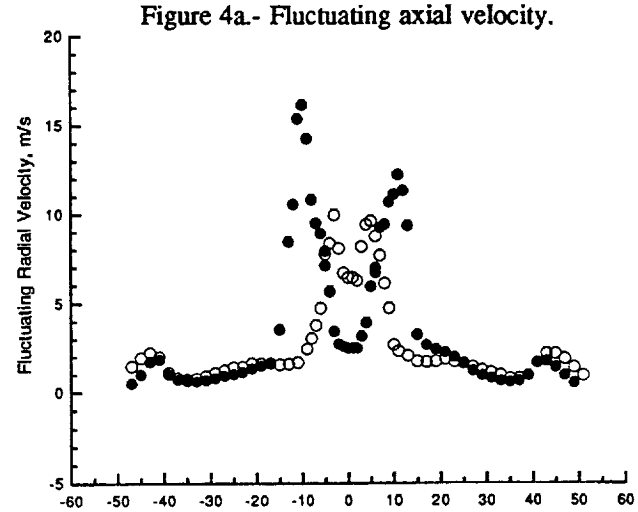

Figure 4b.- Fluctuating radial velocity.

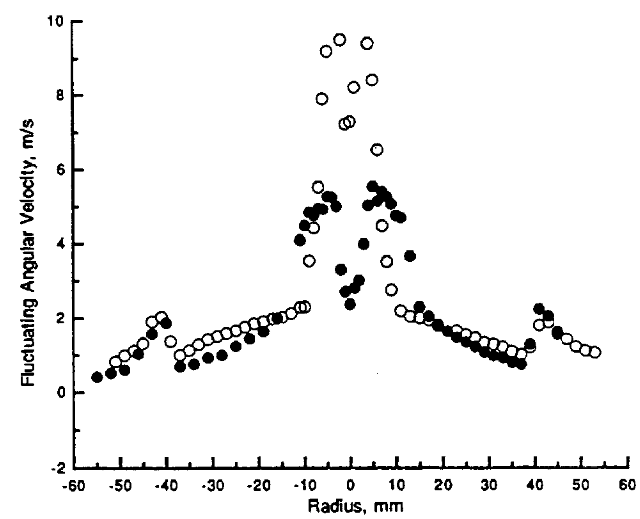

Figure 4c.- Fluctuating angular velocity.

Figure 4.- Gas phase fluctuating velocity at 5 mm downstream.

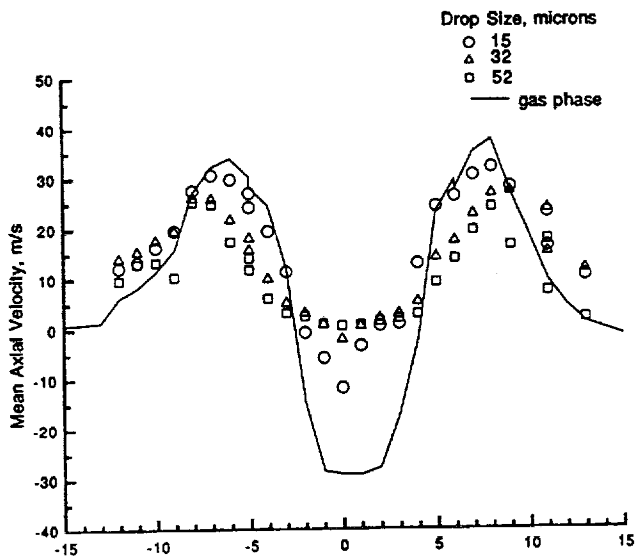

Figure 5a.- Mean axial velocity.

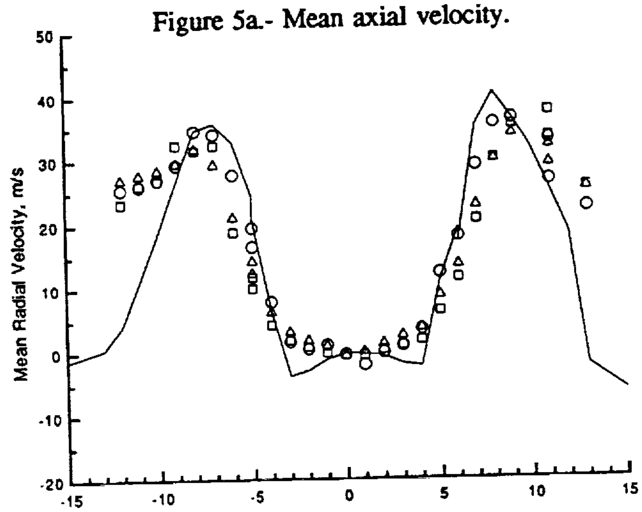

Figure 5b.- Mean radial velocity.

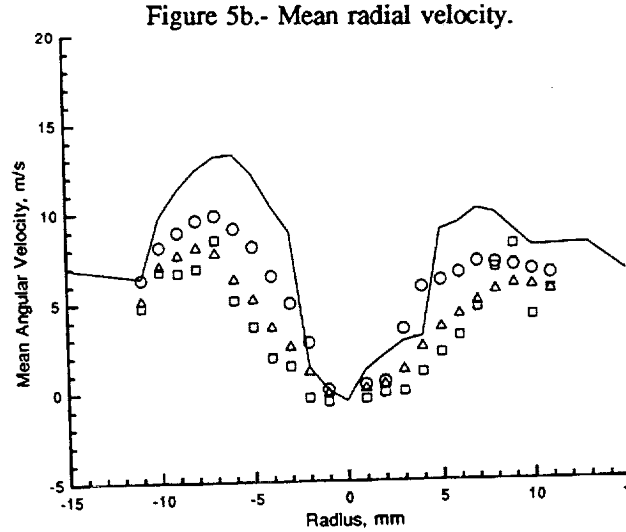

Figure 5c.- Mean angular velocity.

Figure 5.- Drop mean velocity at 5 mm downstream.

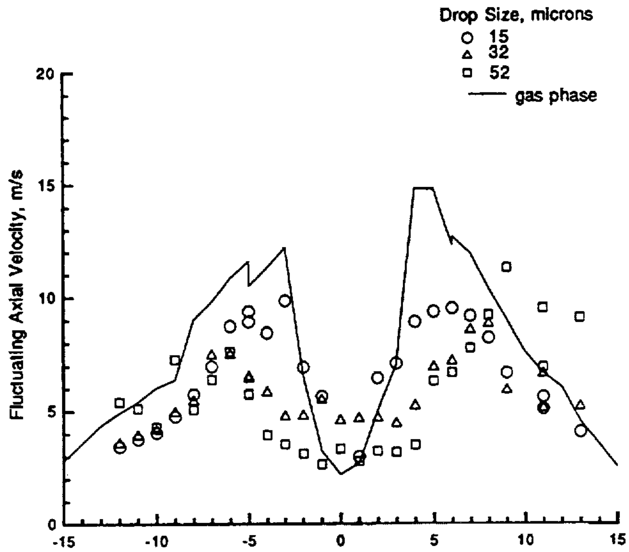

Figure 6a.- Axial velocity.

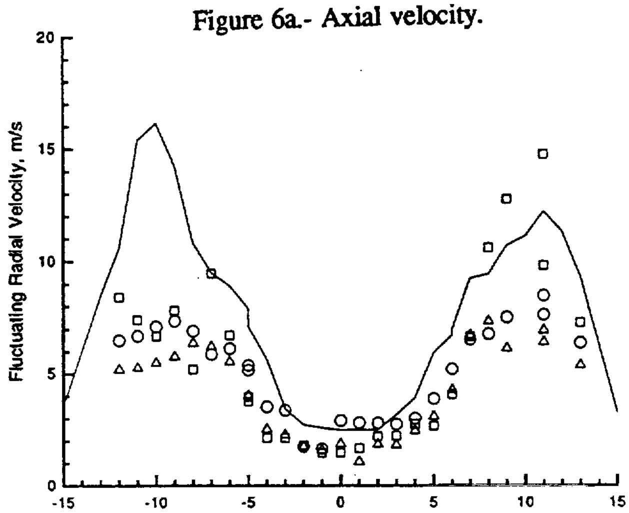

Figure 6b.- Radial velocity.

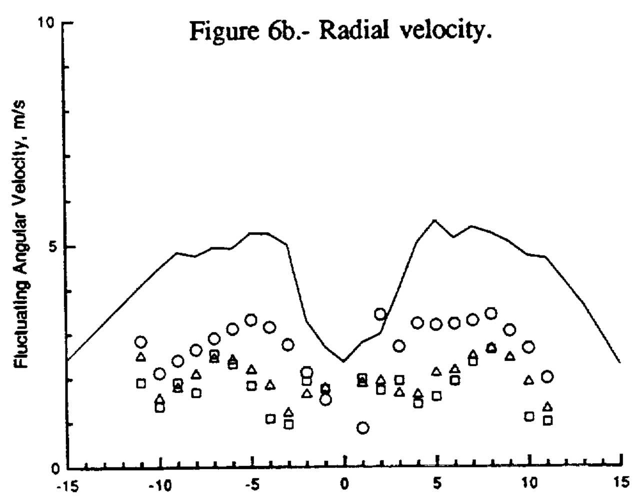

Figure 6c.- Angular velocity.

Figure 6.- Drop fluctuating velocity at 5 mm downstream.

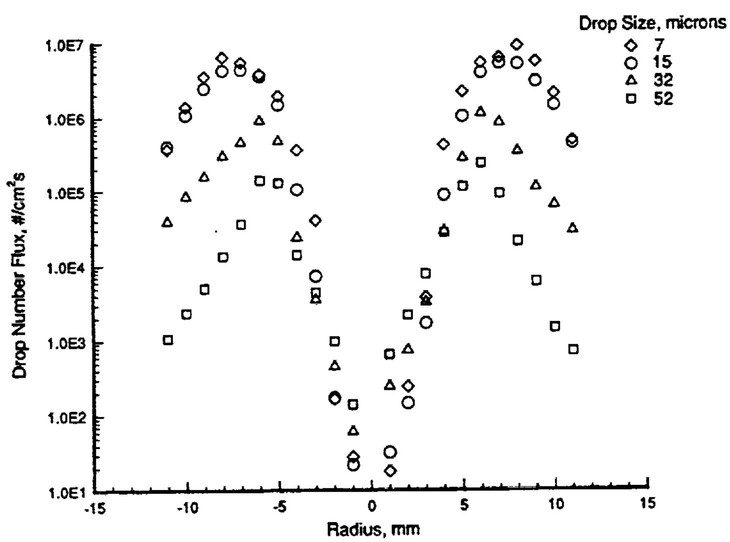

Figure 7.- Drop number flux at 5 mm downstream.

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